F1-096

United States Department of the Interior
U.S. GEOLOGICAL SURVEY

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July 25, 1997

Kate Hansel
CALFED-Bay Delta Program
1416 Ninth Street, Suite 1155
Sacramento, CA 95814

Dear Ms. Hansel:

Enclosed are ten copies of the proposal **Liquefaction Potential of Levee Foundations: Implications for catastrophic levee failure**, which we are submitting in response to the request for proposals under 1997 Category III, ecosystem restoration projects and programs, of the CALFED-Bay Delta Program. We propose to develop 1:24,000 scale maps that illustrate the areal distribution of the hazard posed by earthquake-induced liquefaction of natural deposits in the Delta basin. These maps will be invaluable for assessing the vulnerability of and risk to both levees and other infrastructure in the Delta basin caused by earthquake shaking or strong ground motion.

The enclosed proposal is a collaborative venture by the U.S. Geological Survey and William Lettis & Associates. The proposed investigation also is closely coordinated with the USGS proposal "Strong ground motion maps for evaluation of potential catastrophic collapse from strong earthquakes." If the strong ground motion proposal is funded, we would use its probabilistic ground motions in our study. If the proposal is not funded, we would rely on existing, but less complete, information on seismic sources in and near the Delta basin.

Please contact me should you have any questions concerning the proposed investigation and budget. Please note that the USGS will cost share 40 percent of the salaries of USGS personnel on the project.

Sincerely yours,

Thomas L. Holzer

Thomas L. Holzer, C.E.G.

Executive Summary

Liquefaction Potential of Levee Foundations:
Implications for catastrophic levee failure

Thomas L. Holzer, Robert E. Kayen, and John C. Tinsley, *III*
U.S. Geological Survey

Keith L. Knudsen and William R. Lettis
William Lettis & Associates

The purpose of the proposed collaborative project is to produce a 1:24,000 scale probabilistic map of the potential for earthquake-induced liquefaction of natural deposits in the Sacramento-San Joaquin River Delta. This map is needed to assess the potential for catastrophic failure of levees from earthquake-induced liquefaction of levee foundations. Potential consequences of widespread levee failure and flooding of islands are significant: fresh-water supplies for at least 20 million people may be compromised, economic losses in the Delta may total tens of millions of dollars, and ecosystem restoration projects may experience profound changes in inundation regimes and sediment supply. Thus, an assessment of the risks to Delta levees and infrastructure should be performed before significant resources are devoted to ecosystem restoration projects that are designed without these important data. The presence of nearby seismic sources, shallow groundwater, and loose sandy deposits in the Delta suggests that many levees and other facilities are susceptible to damage caused by liquefaction of underlying materials. The proposed investigation will document the general extent, thicknesses, and engineering properties of sandy natural deposits (those most susceptible to liquefaction) beneath the levees that protect islands in the Sacramento-San Joaquin River Delta. These soil engineering data will be combined with updated surficial geologic maps to produce maps of liquefaction susceptibility. The latter will be combined with newly prepared maps of probabilistic ground motion to generate probabilistic liquefaction potential maps for the Delta basin.

The proposed project consists of three phases: (Phase 1) develop from existing data a three-dimensional geologic model that depicts young, potentially liquefiable materials--this mapping will be used to guide Phase 2; (Phase 2) conduct detailed subsurface exploration at approximately 15 representative sites in the Delta using cone penetration testing, standard penetration testing, and ground penetrating radar to measure engineering properties, thicknesses, and the lateral extent of liquefiable sands; and (Phase 3) revise the Phase 1 geologic model using the Phase 2 field data and develop liquefaction susceptibility and probabilistic liquefaction potential maps. The proposed project will take about 24 months. Development of a three-dimensional geologic model (Phase 1) will take about 4 months, field and laboratory work (Phase 2) will take about 14 months, and preparation of the probabilistic liquefaction potential map (Phase 3) will take about 6 months. All products developed during this project will be published by the U.S. Geological Survey and will be available in digital and paper formats.

One of the four objectives of the CALFED Bay-Delta Program is to reduce the risk to land use and associated activities, water supply, infrastructure, and the ecosystem from catastrophic failure of Delta levees. Available subsurface data are too incomplete to rigorously estimate the actual risk from earthquakes. The data and map products that will be produced in

this investigation will refine the understanding of risk to levees from earthquake-induced foundation failures.

The total amount requested from CALFED is $498,785. This includes $431,949 to the USGS and $66,836 to William Lettis & Associates. The USGS will cost share salaries of USGS personnel by paying 40 percent of assessed salaries, $116,775. Thus, the total project cost is $615,560. William Lettis & Associates will be primarily responsible for Phase 1, the USGS for Phase 2, and both parties will collaborate on Phase 3.

The U.S. Geological Survey/William Lettis & Associates team has extensive experience in the analysis of liquefaction susceptibility and preparation of liquefaction potential maps in northern and southern California. The USGS team also has conducted numerous post-earthquake investigations of liquefaction. Team members have decades of collective experience and regularly interact and cooperate on scientific investigations. William Lettis & Associates staff were encouraged by Mr. Curt Schmutte (California Department of Water Resource) to submit a proposal to characterize the risk to Delta levees and infrastructure from earthquake-induced foundation liquefaction.

Liquefaction Potential of Levee Foundations: Implications for catastrophic levee failure

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and

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Private Entity

RFP Project Group: Type III. Services

Project Description

a. Project Description and Approach

The purpose of the proposed project is to produce a probabilistic liquefaction potential map for natural deposits in the Sacramento-San Joaquin River Delta. Earthquake-induced liquefaction of natural sandy soils beneath levees has been identified as a potential cause of catastrophic failure of levees in the Delta (e.g., USACE, 1987; DWR, 1992). Liquefaction occurs when subsurface sandy materials are shaken strongly by earthquakes and become fluid like. As a result, sands temporarily lose their ability to support surface structures built on them. Structures, such as levees, might either sink into the soil or move laterally into the adjacent channel while ~~riding~~ on the fluidized materials.

This proposed project will document the engineering characteristics, locations and geometry of naturally occurring shallow sand deposits in the Delta and will assess their susceptibility to liquefaction. After compiling and evaluating existing data, we will conduct extensive subsurface exploration at approximately 15 carefully selected sites in the Delta. The exploration will combine (1) drilling and penetration testing to directly measure engineering properties with (2) ground penetrating radar surveys to document the lateral extent of liquefiable materials. Once the detailed geotechnical data are collected and combined with existing data, we will develop probabilistic maps that show the potential for earthquake-induced liquefaction of natural materials. Thus, at the conclusion of this proposed project, resource managers, engineers, local, state and federal agencies, and other interested parties will have the basic data needed to make sound planning and design decisions and to mitigate for the effects of liquefaction of levee foundation materials. The following paragraphs describe the three phases of our proposed approach.

Phase 1. Compile existing information, develop maps and cross sections of Delta surficial geology

We will compile existing surficial geologic, topographic and soils data, subsurface geotechnical data, and historical records of earthquake-induced liquefaction. Using these data, we will develop Quaternary (approximately the last 2 million years) geologic maps and cross sections. Our mapping will consist of (1) interpretation of existing geologic and soils maps, (2) inspection of topographic maps, aerial photography, and early maps of the Delta, (3) geotechnical borings that show the engineering geologic properties of subsurface materials, (4) construction of local Quaternary stratigraphic columns, with age estimates and correlation charts, and (5) reconnaissance-level field investigations. Of greatest use to us will be existing geologic mapping of the Delta (e.g. Atwater, 1982; Helley and Graymer, 1996; Knudsen and Lettis, 1997). These studies, will provide a preliminary stratigraphic framework for Delta Quaternary geology. Using existing geotechnical data, we will develop cross sections and formulate geologic models to be used in predicting both depths to and thicknesses of potentially liquefiable deposits. Units of greatest relevance to liquefaction hazard assessments are typically sandy Holocene (younger than 11,000 years old) deposits.

Much of the Delta is covered by peat. Therefore, a critical consideration is the distribution of sand layers beneath and within the surface peat. Liquefaction of sands down to

about 50 feet can cause significant surface effects. Thus, the potential distribution of sands buried beneath the peat will be addressed before any subsurface investigation is initiated. In the Delta, Atwater (1982) has shown that alluvial fans, sand dunes, abandoned distributary river channels, and flood plains are the primary geologic environments responsible for buried sand layers in the Delta. Our Phase 1 investigation will use existing geotechnical data to characterize both the depth to sand horizons and the abundance of sand layers within peat deposits. These results and the updated maps developed during Phase 1 will be used to guide the detailed field investigations in Phase 2. Selection of approximately 15 sites for detailed investigation in Phase 2 is a critical aspect of Phase 1.

Phase 1 will follow the approach of several recent and ongoing projects funded by the National Earthquake Hazards Reduction Program (NEHRP), in which we have mapped earthquake-induced liquefaction susceptibility and-or Quaternary geology in northern and southern California. Our maps (e.g., Lettis, 1982; Tinsley and others, 1985; and Tinsley and Dupré, 1992) are used by state and local agencies to identify areas of hazards, plan additional studies, and guide policy decisions. William Lettis & Associates staff presently are developing Quaternary geologic maps and liquefaction susceptibility maps of parts of the Delta under separate funding arrangements with the NEHRP. Thus, the costs of conducting Phase 1 will be shared by these separate research grants.

Phase 2. Field and laboratory investigations

To evaluate the liquefaction susceptibility of geologic map units, and the variability within map units, we propose a detailed field investigation. Phase 2 will involve characterization of subsurface deposits by both drilling and ground penetrating radar. We propose to acquire approximately 150 cone penetration tests (CPT), distributed approximately equally among 15 representative sites. The sites will be selected based on our evaluation of geologic conditions performed during Phase 1 and criticality of the site for assessing levee stability. CPT soundings, which involve measuring the resistance of a 10-cm^2 probe as it is pushed through the soil, provide a continuous log of the mechanical properties of subsurface materials. CPT soundings are extremely sensitive to variations in soil texture (grain size and distribution). CPT exploration will be used to estimate directly the liquefaction susceptibility of sandy materials and to document the thickness of liquefiable materials at each site (Robertson and Campanella, 1985). Correlations between adjacent soundings will provide information on the lateral continuity of sand beds. One significant uncertainty in analyses of this type is the dynamic response of peats. Some research suggests that peat soil are highly nonlinear (Seed and Idriss, 1970). Thus, the position of the liquefiable sand layers relative to the peat layers is important to characterizing the levels of shaking the sand horizons will experience. For example, if the sands are located under the peat, the dynamic response of the peat is irrelevant to ground motion considerations for liquefaction. However, if the peat has sand horizons within or above it, the response of the peat is important and will need to be accounted for in Phase 3.

CPT exploration will be augmented with 2 drill holes at each of the 15 sites. The drilled holes will include standard penetration tests (SPT) in sandy horizons to confirm the soil texture interpretations inferred from the CPT. The SPT, which is a standardized soil testing and sampling technique, is also the "industry" standard for evaluating liquefaction

susceptibility of sandy materials (Seed and others, 1985). Thus, it provides an independent check on the estimates of liquefaction susceptibility inferred from the CPT data. We also will obtain undisturbed soil samples with Shelby tubes and log them with a gamma ray whole-core section logger. This logging technique measures the void ratio of samples, which is useful for evaluating their potential for flow failure during liquefaction.

We also will conduct field measurements of soil strength. In situ shear strengths of the natural soils--peat, sand, silt, and clay--will be measured in the drilled holes to a depth of about 20 feet with a field shear vane. Laboratory vane shear measurements will be made in Shelby tube samples. Measurements will include both peak and residual strengths. These measurements provide an estimate of the dynamic strength of these soils under earthquake loading because the rate of loading with the vane shear is similar to earthquake loading. Residual strengths also are useful for assessing the potential for flow failure after initial liquefaction.

To economically and rapidly assess the lateral extent and thickness of potentially liquefiable deposits, we will use ground-penetrating radar (GPR) technology to image subsurface materials. GPR is a relatively new technology that employs radio waves to non-destructively probe the shallow structure of the Earth in a manner analogous to seismic reflection profiling. For delta deposits, where biogenic methane is likely to occur, GPR is capable of imaging deep reflectors where conventional seismic-reflection profiling techniques would fail due to the presence of gas. Our present experience surveying delta deposits in Puget Sound, WA, indicates that with GPR we can penetrate to approximately 60 ft in sandy and fine-grained, water-saturated sediment with vertical resolution of about ±3 ft. We will acquire digital GPR profiles both along and orthogonal to the alignment of CPT and SPT sites taken at study sites in the Delta. The intent of this work will be to develop detailed intra-site stratigraphy where subsurface probing with in situ penetration equipment has given point location 'ground-truth' data on soil properties. GPR also will be utilized to further characterize the thickness and lateral extent of potentially liquefiable layers. Imagery will be collected at sites of historic liquefaction to resolve venting structures and discontinuities that occur during sand-blow expulsion of fluid, fissuring, and lateral spreading of the ground. We will use measurements of the unit thickness and lateral extent at these locations to model the local liquefaction potential at our 15 sites. These data, in combination with our Quaternary geologic maps and cross sections, will then be used in a statistical model for assessing the regional probability of liquefaction occurrence in the delta.

Completion of Phase 2 will be primarily the responsibility of the USGS team members. Phase 2 will follow the approach of several recent and ongoing USGS NEHRP projects, in which extensive subsurface exploration programs were conducted that involved hundreds of exploratory borings and soundings. These programs were conducted to explore sites of ground failure in young geologic deposits caused by the 1989 Loma Prieta and 1994 Northridge earthquakes.

Phase 3. Develop liquefaction susceptibility and probabilistic liquefaction potential maps

The final step in the proposed investigation is the preparation of 1:24,000 scale probabilistic liquefaction potential maps for natural deposits in the Delta. The Quaternary

geologic mapping used to plan the site investigations will be reexamined and modified in view of the subsurface exploration program. These maps, with results of the detailed field investigation incorporated, will be the basis on which we will develop liquefaction susceptibility and potential maps. The CPT and SPT testing results will be used to compute the liquefaction susceptibility of individual geologic units. The Quaternary geologic maps will then be transformed into liquefaction susceptibility maps. Next, we will develop probabilistic liquefaction potential maps by combining the liquefaction susceptibility maps with probabilistic ground motion maps. If the proposed USGS investigation "Strong ground motion maps for evaluation of potential catastrophic levee collapse from strong earthquakes" is funded by CALFED, we will use and modify their probabilistic ground motions by weighing peak accelerations to a magnitude 7.5 earthquake (Idriss, 1985). This modification is necessary is to take into account the effect of earthquake magnitude on estimated liquefaction resistance. If the new ~~USGS~~ estimates of ground motions are not available, we will use published probabilistic ground motions (Frankel and others, 1996). We anticipate producing several probabilistic liquefaction maps that would be based on different sets of assumptions about the dynamic response of peat. Since these maps will be produced using a geographic information system, the multiple calculations are not significant.

Both the USGS and WLA have extensive experience with the production of liquefaction maps and will cooperatively develop the liquefaction maps. WLA will be primarily responsible for producing Quaternary geologic maps. USGS and WLA will collaborate on the liquefaction susceptibility maps. USGS team members will be primarily responsible for the probabilistic liquefaction potential maps. All products will be peer reviewed by scientists within the USGS.

b. Location

We will produce maps of, and perform field investigations in the Delta basin in Contra Costa, Sacramento, San Joaquin, Solano, and Yolo counties.

c. Expected Benefits

Improve quantification of the risk to land use and associated activities, water supply, and infrastructure, and the ecosystem from catastrophic, earthquake-induced failure of foundations of Delta levees. Products developed during this project will be useful in designing ecosystem restoration projects and in guiding the long-term Delta planning and alternatives analysis process.

d. Background and Technical Justification

Earthquake-induced liquefaction of natural sandy soils beneath levees has been identified as a potential cause of catastrophic failure of levees in the Delta in several studies including the 1992 phase I investigation by the California Department of Water Resources (DWR, 1992) and the 1987 investigation by the U.S. Army Corps of Engineers (USACE, 1987). Because the Delta is subject to strong ground motion from both distant and local earthquake sources, the possibility of multiple simultaneous catastrophic failures of levees and multiple island flooding is a serious concern that needs to be resolved. The extent of the

liquefaction hazard is poorly known. A preliminary assessment of the liquefaction hazard in the Delta by the California Department of Water Resources, which relied on incomplete existing information, concluded that subsurface information was not adequate to evaluate the hazard. By contrast, (Volpe and others, 1992) conducted a probabilistic liquefaction hazard assessment at 18 sites along the route of the Mokelumne Aqueduct in the Delta. They concluded that 9 of the sites had a 50 percent probability of liquefaction in the next 30 years.

e. Proposed Scope of Work

The work will be conducted in three phases. Phase 1 will be a detailed review of existing investigations, and integration of existing data into a geologic framework and series of maps and cross sections of the Delta, which will be used to select approximately 15 sites for concentrated investigation. Phase 2 will consist of detailed subsurface investigations at the 15 selected sites. Phase 3 will consist of using the geotechnical data from Phase 2 to calibrate and, where appropriate, to modify the geological framework and maps from Phase 1, and to generate a probabilistic liquefaction potential map for the Delta basin.

f. Monitoring and Data Evaluation

Data collected and produced in this investigation will consist of descriptions of the physical properties and distribution of subsurface materials susceptible to earthquake-induced liquefaction. Data will be archived in Techbase®, a geotechnical database program, which is compatible with ArcInfo®, a geographic information system. Data will be published in peer-reviewed open-file reports by the USGS and will be available in both digital and paper formats. Liquefaction potential maps will be published as USGS I series maps and will be digitally available as Arcinfo® files.

g. Implementability

Once sites for soundings and borings are selected, permission from individual land owners will be requested before any field work is conducted. All holes will be backfilled with grout upon completion.

Mr. Curt Schmutte of the California Department of Water Resources encouraged us to submit this proposal.

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Costs and Schedule to Implement Proposed Project

a. Budget costs

The amount requested from CALFED is $498,785. The total proposed project cost is $615,560 of which $116,775 will be cost shared by the USGS. Table 1 summarizes the proposed costs and costs sharing.

Table 1. Project costs and USGS cost sharing

USGS costs	$548,724
Lettis & Associates costs	$66,836
Subtotal	$615,560
USGS cost sharing	($116,775)
CALFED proposed request	**$498,785**

USGS cost sharing consists of 40 percent of USGS assessed salary. Production of a liquefaction potential map for the Delta is consistent with the mandate to the Federally funded National Earthquake Hazards Reduction Program (NEHRP) to reduce the impact of earthquakes on society. CALFED funding is required because NEHRP currently emphasizes urban areas and it is unlikely that the proposed mapping project would be funded through NEHRP funding. Incremental funding by CALFED for each phase is possible because the phases will be conducted sequentially. As a Federal agency, all procurement and contracting at the USGS will follow appropriate Federal regulations.

Budget Summary

	Agency/Company	Total cost
Phase 1	USGS	$43,945
	Lettis & Associates	$41,164
Phase 2	USGS	$342,031
	Lettis & Associates	$5,284
Phase 3	USGS	$162,748
	Lettis & Associates	$20,388
	Subtotal	$615,560
	USGS cost sharing	($116,775)
	CalFed cost	$498,785

William Lettis & Associates

Proposed Budget: Liquefaction Potential of Levee Foundations

Project Phase	Personnel	Direct Labor Hours	Direct Salary and Benefits	Labor Overhead, G&A & Fee	Service Contracts	Material and Acquisition Contracts	Miscellaneous and other Direct Costs	Total Costs
Phase 1	K. Knudsen	240	$7,435					
	W. Lettis	64	$4,483					
	Staff Geologist	200	$4,850					
	Clerical	0	$0					
	Draftsperson	40	$1,132					
			$17,900	$20,299	$0	$0	$2,965 (A)	$41,164
Phase 2	K. Knudsen	40	$1,239					
	W. Lettis	16	$1,121					
	Staff Geologist	0	$0					
	Clerical	0	$0					
	Draftsperson	0	$0					
			$2,360	$2,676	$0	$0	$248 (B)	$5,284
Phase 3	K. Knudsen	120	$3,718					
	W. Lettis	40	$2,802					
	Staff Geologist	40	$970					
	Clerical	24	$582					
	Draftsperson	40	$1,132					
			$9,203	$10,436	$0	$0	$748 (C)	$20,388

TOTAL	$66,835.47

(A) Mileage (2000 mi), large format graphics and scanning, maps, software (ArcView 3.0 mapping module)

(B) Mileage (800 mi)

(C) Mileage (800 mi), large format graphics and scanning

U.S. Geological Survey
Proposed Budget: Liquefaction Potential of Levee Foundations

Project Phase	Personnel	Direct labor pay periods	Direct labor hours	Direct salary and benefits	Labor over-head, G & A & fee	Service contracts	Material and Acquisition Contacts	Micellaneous and other direct costs	Per diem	Total costs
Phase 1	T. Holzer	1	80	$4,528						$4,528
	J. Tinsley	3.1	248	$11,418					$4,030	$15,448
	R. Kayen	1	80	$3,450						$3,450
	B. Atwater	1	80	$3,486						$3,486
	M. Bennett	1	80	$2,550					$1,300	$3,850
	C. Criley	0	0							$0
	Total	7.1	568	$25,432	$0	$0	$0	$0	$5,330	$30,762
Phase 2	T. Holzer	1	80	$4,528						$4,528
	J. Tinsley	3	240	$11,050						$11,050
	R. Kayen	6	480	$20,698					$1,040	$21,738
	B. Atwater	0	0							$0
	W. Barnhardt	4	320	$8,172					$1,040	$9,212
	M. Bennett	8	640	$20,397						$20,397
	C. Criley	17	1360	$22,658						$22,658
	ECO tech	26	2080	$35,000						$35,000
	CPT					$80,000				$80,000
	SPT						$1,140	$4,500	$11,700	$17,340
	GPR					$17,500				$17,500
	Total	65	5200	$122,502	$0	$97,500	$1,140	$4,500	$13,780	$239,422
Phase 3	T. Holzer	4	320	$18,112						$18,112
	J. Tinsley	4	320	$14,733						$14,733
	R. Kayen	4	320	$13,798						$13,798
	B. Atwater	0	0							$0
	M. Bennett	1	80	$2,550						$2,550
	C. Criley	0	0	$0						$0
	GIS Tech (11)	4	320	$7,231						$7,231
	computer							$5,000		$5,000
	Map publication							$52,500		$52,500
	Total	17	1360	$56,424	$0	$0	$0	$57,500	$0	$113,924
			Total	$204,357						

Subtotal	$384,107
Assessment	$164,617
USGS subtotal	**$548,724**
USGS cost sharing	**($116,775)**
CALFED cost (USGS only)	**$431,949**

US Geological Survey Itemized Expenses for CALFED Delta liquefaction investigation

Phase 1

$4,030	Per diem, J. Tinsley, 31 days at $130/day, reconn, flagging, permitting
$1,300	Per diem, M. Bennett, 10 days at $130/day, reconn, flagging, permitting
$5,330	Subtotal

Phase 2

$1,040	Per diem, R. Kayen, 8 days at $130/day, field work with radar
$1,040	Per diem, W. Barnhardt, 8 days at $130/day, field work with radar
$80,000	Service contracts, CPT, includes sounding, grouting, and travel
$1,140	Material and acquisition contracts, SPT, shelby tubes, 120 at $9.50
$4,500	Miscellaneous and other direct costs, SPT, drill rig maintance, gas, oil, grout
$11,700	Per diem, SPT, 3 people, 30 days at $130/day, drilling/sampling
$17,500	Service contacts, GPR, 15 days at $1,100/day, and computer hard drive
$116,920	Subtotal

Phase 3

$52,500	Miscellaneous and other direct costs, 21-1:24,000 maps at $2,500/each
$5,000	Miscellaneous and other direct costs, miscellaneous computer/ programs
$57,500	Subtotal

b. Schedule Milestones

The project is anticipated to take approximately two years. Phase 1, synthesis of existing information and planning, will take about 4 months. Phase 2, field operations, laboratory analyses, data processing will take about 14 months. Phase 3, characterization of liquefaction susceptibility of geologic units and production of the probabilistic liquefaction potential map will take about 6 months.

c. Third Party Impacts

There are no known or anticipated third party impacts that would result from implementation of this project.

Applicant Qualifications

Dr. Thomas L. Holzer is a Research Engineering Geologist with the USGS Western Earthquake Hazards Team and is a Certified Engineering Geologist in the State of California. He conducted extensive geotechnical investigations of liquefiable deposits in the San Francisco and Monterey Bay regions following the 1989 Loma Prieta earthquake and in Southern California following the 1994 Northridge earthquake. Dr. Holzer has conducted numerous case histories of liquefaction including the first instrumented measurements of liquefaction of natural deposits. He received his doctoral degree from Stanford University. Dr. Holzer will be responsible for project management, and will provide technical oversight for all investigations conducted by the USGS team members. He also will oversee development of the probabilistic liquefaction potential map.

Dr. Robert E. Kayen is a Research Civil Engineer with the USGS Western Coastal and Marine Geology Team and is a registered Professional Civil Engineer in the State of California. He has conducted integrated sedimentological, geophysical, and geotechnical investigations in the San Francisco Bay region including studies of the effects of the Loma Prieta earthquake on the liquefaction potential of coastal soil deposits. Kayen has developed a new methodology for assessing liquefaction potential of soil deposits based of the Arias intensity of strong ground motion. He received his doctoral degree from the University of California at Berkeley. Dr. Kayen will be responsible for the GPR investigation.

Dr. John C. Tinsley, III, is a Research Quaternary Geologist with the USGS Western Earthquake Hazards Team. He has broad experience in mapping Quaternary geologic units and has prepared liquefaction potential maps for several areas in both southern and northern California. He has also been intimately involved in extensive subsurface investigations of Quaternary deposits that liquefied and failed during the 1989 Loma Prieta and 1994 Northridge earthquakes. He received his doctoral degree from Stanford University. Dr. Tinsley will be responsible for design of the field exploration program and the liquefaction susceptibility characterization of the geologic units.

Mr. Keith L. Knudsen is a Project Geologist with William Lettis & Associates of Walnut Creek, California. He is a Certified Engineering Geologist in the State of California and has more than 6 years of professional experience conducting geologic and geomorphic

studies. Mr. Knudsen is currently funded by the National Earthquake Hazard Reduction Program, together with the Association of Bay Area Governments, to develop a liquefaction susceptibility map of the nine-county San Francisco Bay area for publication on the World Wide Web. He received his masters degree from Humboldt State University. Mr. Knudsen will be responsible for project management of the William Lettis & Associates' contribution to the project.

Dr. William R. Lettis is President and Principal Geologist with William Lettis & Associates. He is a Certified Engineering Geologist in the State of California and has over 18 years of professional experience conducting earthquake-related studies. Dr. Lettis currently is a Director for CONCERT, the Coordinating Organization for Northern California Earthquake Research and Technology, and recently served on the California Division of Mines and Geology's subcommittee on liquefaction hazards. He received his doctoral degree from the University of California at Berkeley. Dr. Lettis will be responsible for ensuring accomplishment of technical objectives and technical oversight of the William Lettis & Associates' contribution to the project.

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